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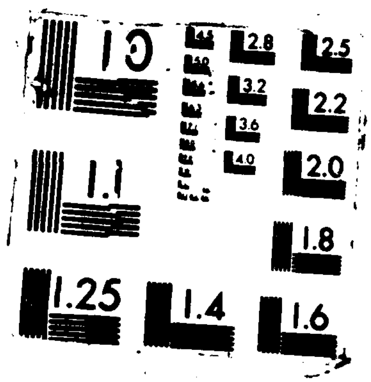
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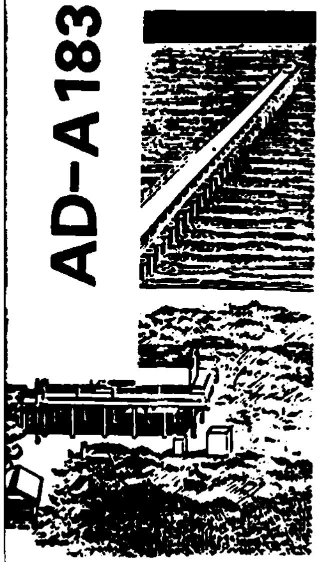

INSTRUCTION REPORT CERC-86-2

A USER'S GUIDE TO SHALWV: NUMERICAL MODEL FOR SIMULATION OF SHALLOW-WATER WAVE GROWTH, PROPAGATION, AND DECAY

Report 2
SHALWV--HURRICANE WAVE MODELING AND VERIFICATION

by

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June 1987

Report 2 of a Series

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Civil Works Research Work Unit 31592

87

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) Instruction Report CERC-86-2	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION USAEWES, Coastal Engineering Research Center 6b OFFICE SYMBOL (If applicable) WESCV	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO | PROJECT NO | TASK NO | WORK UNIT ACCESSION NO 31592

11 TITLE (Include Security Classification)
A User's Guide to SHALWV: Numerical Model for Simulation of Shallow-Water Wave Growth, Propagation, and Decay; Report 2: SHALWV--Hurricane Wave Modeling and Verification

12 PERSONAL AUTHOR(S)
Jensen, Robert E.; Vincent, Charles E.; Abel, Charles E.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Report 2 of a series	FROM ____ TO ____	June 1987	52

16 SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Hurricane wind fields; SHALWV (computer program); Numerical simulations; Water waves

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report is the second in a series of user's guides to SHALWV, a numerical model that simulates shallow-water wave growth, propagation, and decay in a directional spectrum over an arbitrary bathymetry. The original report (Instruction Report CERC-86-2) was titled "A User's Guide to SHALWV: Numerical Model for Simulation of Shallow-Water Wave Growth Propagation, and Decay." Future enhancements to the model will be added to the series.

The report herein presents a numerical model for estimating hurricane wave conditions in arbitrary water depths, including a discussion of wind input to SHALWV, changes in the model, and model verification. The major changes made to the model allow a better representation of wind wave growth in rapidly turning winds.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code) | 22c OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

PREFACE

This report was prepared at the Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station (WES) under Civil Works Research Unit 31592, "Wave Estimation for Design," Coastal Flooding and Storm Protection Protection Program, Coastal Engineering Area of Civil Works Research and Development, Office, Chief of Engineers (OCE). The Technical Monitors from OCE were Messrs. John H. Lockhart, Jr., and John G. Housley.

This report, the second in a series, describes modifications to the numerical model SHALWV to allow simulations of hurricane conditions and provides verification of the model against related storms of record and idealized growth conditions.

This report was prepared by Drs. Charles L. Vincent, Program Manager, CERC, Robert E. Jensen, Research Hydraulic Engineer, and Charles E. Abel, Research Physical Oceanographer, Coastal Oceanography Branch (COB), CERC, under direct supervision of Dr. Edward F. Thompson, Chief, COB, and Mr. H. Lee Butler, Chief, Research Division. General supervision was provided by Mr. Charles C. Calhoun, Jr., Assistant Chief, and Dr. James R. Houston, Chief, CERC. This report was edited by Ms. Shirley A. J. Hanshaw, Information Products Division, Information Technology Laboratory, WES.

The authors extend special acknowledgment to Dr. Abel, our colleague and co-author, who generated all hurricane wind fields for the wave simulations. Dr. Abel passed away on 19 April 1987.

Commander and Director of WES during report publication was COL Dwayne G. Lee, CE. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
knots (international)	0.5144444	metres per second
miles (US nautical)	1.852	kilometres

A USER'S GUIDE TO SHALWV: NUMERICAL MODEL FOR SIMULATION OF SHALLOW-WATER WAVE GROWTH, PROPAGATION, AND DECAY

SHALWV--HURRICANE WAVE MODELING AND VERIFICATION

PART I: INTRODUCTION

Background

1. Hurricanes produce large waves that are a major component of the design wave statistics for much of the Atlantic Coast and all of the Gulf of Mexico. Tropical cyclones in the Pacific are an important design consideration in the Trust Territories as well as in Hawaii. Even in Southern California, swell out of Eastern Pacific hurricanes influences the wave climate. Wave measurements in major hurricanes show significant heights in excess of 12 m and individual wave heights of more than 21 m. An ability to accurately estimate hurricane wave conditions, especially on the continental shelf and in coastal regions, is a necessity for optimal design of US Army Corps of Engineers projects on many US shorelines.

2. Hurricane wave conditions are relatively difficult to estimate for two reasons. First, the relatively small size of the systems (radius to maximum winds typically 15 to 30 nautical miles*) produces extreme wind speeds (greater than 64 knots) with very rapid shifts in the wind direction. Second, the small size of the systems also creates large gradients in the wave characteristics in both an alongshore and offshore-onshore direction, compounded by water level variations as large as 3 m or more at the coast because of surge.

3. The hurricane wave estimation method recommended by the Shore Protection Manual (SPM) (1984) is based on scaling of the Sverdrup-Munk-Bretschneider wave growth curves. The SPM nomogram provides an estimate of the significant wave height by a spatial scaling function based on the radius parameter of the storm. This approach has been very useful over the past several decades, and efforts have been made to update it (Ross 1979). The principal disadvantages of this method are that it (a) does not allow for

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

representation of any wind field variations in a storm, (b) does not specify the separation of wind sea* and swell waves,** and (c) gives an incorrect estimate of wave direction in certain regions of the storm.

4. The evolution of numerical wave models for estimating wave characteristics, including one- and two-dimensional (1-D and 2-D) spectra, has significantly improved the ability to model realistic wave generation scenarios in deep water. An intercomparison of several operational wave models for two simple and generalized hurricane cases showed considerable differences among modern wave model results. Originally developed for extratropical storm systems, the Sea Wave Modeling Project (SWAMP) tests were used to determine the reaction of the models to idealized hurricane situations (The SWAMP Group 1985). There was insufficient information to indicate definitively which, if any, of the models were correct. However, notably several of the models have been used by their developers to hindcast selected hurricanes of record reasonably accurately, at least in terms of significant wave height or wave period (e.g. Cardone, Pierson, and Ward (1976)).

5. Time-dependent numerical models require very detailed specification of the wind field in time and space to produce estimates of the directional spectrum of the wave field. In a generalized sense, a hurricane wind field is no more than a very small and intense asymmetric low pressure center. Rather than generate a unique wave model to solve these special cases, it is appropriate to modify current spectral wave models to accomplish the task of estimating wave conditions under severe tropical depressions.

Model Modification

6. The report herein provides an update to and enhancement of the model presented in "A User's Guide to SHALWV: Numerical Model for Simulation of Shallow-Water Wave Growth, Propagation, and Decay" (Hughes and Jensen 1986) by presenting a numerical model for estimating hurricane wave conditions in water of arbitrary depth. The major changes made to the model allow a better representation of wind wave growth in rapidly turning wind fields. It includes

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* Wind sea is defined as a wave train which is actively growing because of the influence of local winds.

** Swell waves are wave trains not under active growth, although they may be propagating in an area of strong local winds.

discussion of wind input to the model, changes in the model, and model validation. The changes to the model have all been internal, and there are no differences to model input specifications from those discussed in Hughes and Jensen (1986).

7. SHALWV was modified because it is a time-dependent model including shallow-water transformation mechanisms. With the hurricane related revisions, SHALWV can handle both tropical and extratropical wind fields without the operator of the model requiring additional information that input winds are of hurricane intensity.

PART II: WIND FIELD INPUT

8. The accuracy of wave estimates is in large part determined by the adequacy of the wind input.* For a hurricane, development of a wind field is more difficult than for extratropical storms. Several approaches can be used. For the case of a hypothetical storm, a method such as the Standard Project Hurricane (US Department of Commerce 1979) moving along a specified storm track may be applied. This method utilizes synthesized hurricanes to determine design conditions, but, for the most part, it will not yield realistic conditions that can be obtained from simulation of historical storms. Representation of historical storms generally requires use of a wind model that can allow computation of realistic wind fields from the more anomalous pressure structures of historical storms.** However, the improved approximation is accompanied by increased complexity requiring not only a more complex wind model but also a significant amount of meteorological insight. The hurricane is represented as a moving vortex embedded in an ambient pressure field. Various degrees of complexity of radial asymmetry of the pressure field can be accommodated if sufficient data are available to allow accurate determination of the pressure field parameters. The model incorporates a planetary boundary layer model to estimate near surface wind velocities. Establishment of the time-history of the parameters needed to drive this wind model requires considerable effort, but the result is a state-of-the-art representation of the hurricane wind field that has been used in a number of different investigations to achieve good wind field matches within the relative accuracy of available data.

9. Although the Cardone Planetary Boundary Layer Model (PBLM) is state of the art, measurements of hurricane wind fields using advanced technology

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* SHALWV requires a time-history of the hurricane winds specified on the same spatial grid as the bathymetry and all input conditions. All wind information must be set at a 10-m elevation and adjusted for boundary layer stability effects to be an equivalent neutral wind speed. The file structure is specified in Hughes and Jensen (1986).

** V. J. Cardone et al. prepared an unpublished report titled "Unified Program for the Specification of Hurricane Boundary Layer Winds Over Surfaces of Specified Roughness" for the Hydraulics Laboratory at the US Army Engineer Waterways Experiment Station in 1981. The model is discussed in this report by Cardone et al.

indicate the structure of hurricanes is often far more complicated than can be represented even with the PBLM. For example, some hurricanes exhibit double eye-like features that are not readily fit by simple radial pressure fields. Other storms exhibit significant asymmetries that cannot be represented by a smoothly varying exponential decay in the pressure field. Furthermore, the region more than 3 or 4 radii from the storm canter can be strongly influenced by more complex pressure gradients relative to the fairly simple form used in the PBLM. As a result, waves generated in the far field of the hurricane can deviate significantly in magnitude and direction from those observed. These are not the regions of extreme waves but are often the areas where wave measurements have been made.

10. Hurricane storm tracks are probably no more accurate than 5 nautical miles because the center of a storm is difficult to pinpoint. In many cases this inaccuracy leads to an uncertainty of 15 to 35 percent of where the highest winds will be located. For many storms these deficiencies can be overcome if sufficient other data are available to allow calibration of the wind field. However, for most storms in the historical record, the information is incomplete; consequently, the level of uncertainty is high.

11. Verification of a hurricane wave model is difficult because it is often unclear whether differences between prediction and observation result from inadequacies in the wave model or a poor prediction of the winds. For example, wind velocities in hurricanes are large so an error of 10 to 15 percent in the winds can easily result in at least a 1-m difference in wave height and several seconds in peak spectral wave period.

12. Selection of a proper simulation time requires care in order to depict accurately key subevents in the hurricane. Waves generated in a hurricane may have periods as long as 14 to 17 sec. These waves can move out of the storm region at speeds greater than 20 knots which is often twice the speed of storm movement. Thus, swell can outrace a storm area reaching coastal areas a day before the most intense storm conditions can pass a site. Furthermore, accurate wind field estimates are needed because errors in wind speed or direction can cause the outflowing swell to propagate at an angle, possibly missing an area of interest. If prediction of the forerunning events is needed, a storm may have to be simulated 3 days or more prior to arrival at the site of interest. In the Gulf of Mexico, this may not be necessary because of the limited size of the water body.

13. The most severe wave conditions near the center of the storm may be predicted with a smaller period of simulation because the waves are typically duration limited. In such a simulation, it must be stressed that wave conditions leading up to the peak conditions may be significantly misestimated. In a similar fashion, the simulations away from the storm center may be distorted and have less swell than actually occurs. Thus, establishment of the data requirements can influence the length of time that must be simulated. In general it is recommended that as long a simulation as possible be made with care taken to represent the wind field on the outer boundary of the storm.

PART III: MODIFICATIONS TO SHALWV

14. SHALWV is a pseudodiscrete spectral model. Information is stored in a discrete matrix of frequency and direction bands for each computation point, but the sources and sinks in the energy balance equation associated with energy input, transfer, and dissipation are represented in a parameterized fashion. For a growing wind sea, the value of the peak frequency of the spectrum and a number of parameters for spectral shape are calculated through a series of parametric equations (Hughes and Jensen 1986). The equations estimate the rate of wave growth and changes in spectral shape without extraordinarily complicated calculations of the details of specific source/sink mechanisms. The parametric approach is utilized because the mathematical representations of the most important source functions are not particularly accurate and are often computationally awkward. To compensate for this deficiency, most wave models force some part of the spectral shape by a spectral shape equation. The parameterizations used in SHALWV appear to represent the basic patterns of wave growth and energy transfer in a less complicated manner and yield accurate representations of historical events (as will be discussed in a later section of this report). Recently, a more rigorous approach has been developed for modeling the source/sink mechanisms (Hasselmann and Hasselmann 1985b), but models based on this approach are just becoming operational and require very extensive computer resources. Such modeling approaches will be considered in the future as a possible update to SHALWV.

15. The significant enhancement to SHALWV to allow hurricane simulation involves treatment of a rapidly changing wind field. SHALWV was originally developed under assumptions of a slowly changing wind field. A hurricane passage of the eye across or near a site can result in a nearly 180-deg turn in the wind with wind speeds remaining high. Thus, the wind can turn and develop waves in a direction opposite to what had just been the wind sea a short time before. This occurrence will result in two distinct wave populations: wind sea traveling with the wind and swell (the fossil wind sea) traveling (for this example) in an opposite direction (Figure 1). As previously mentioned, this is a situation in which neither definitive field nor laboratory information is available. The approaches employed by modelers are made on the basis of their interpretation of air-sea interaction and spectral wave mechanics.

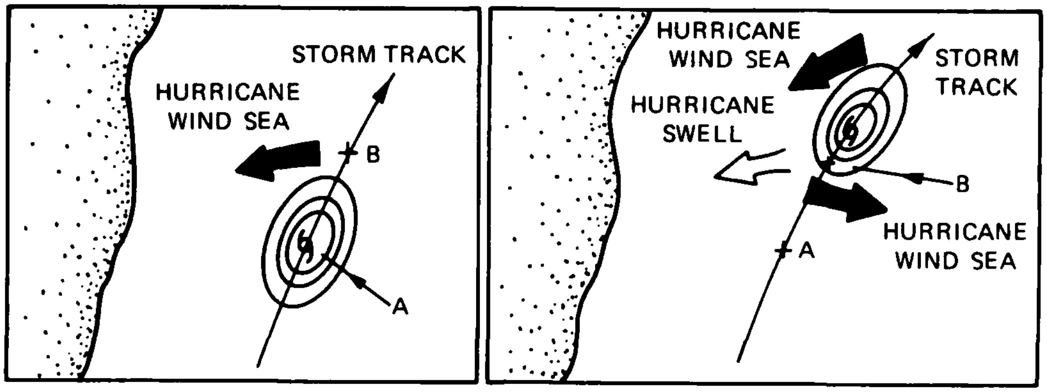


Figure 1. Schematic representation of rapidly turning winds

16. The method utilized here draws on the results of the Exact-Nonlinear Wave Model of Hasselmann and Hasselmann (1985b) and Hasselmann et al. (1985). During the movement of a hurricane past a particular location, the turning winds will create short waves that evolve into a new wind sea while the fossil waves become swell. The nonlinear calculations suggest that the difference in wave angle and peak frequency between the new wind sea and the old waves allows the new waves to develop without interacting with the older waves. This development will continue until the new wind sea approaches the peak frequency of the older waves. At that point the new wind sea is steeper than the fossil waves and absorbs their energy.

17. This behavior is approximated in SHALWV via the following procedure. There are four possible solutions to estimate growth sequences. At each grid point and each time-step, the mean direction of the existing wind sea is compared to the new wind direction. If the absolute difference between the wind sea and new wind direction is less than 90 deg, the wind sea will continue to grow based on the new wind conditions. If the wind sea and new wind direction are greater than 90 deg, a second series of criteria is employed. The algorithm checks the wind and wave directions in the new upwind direction from the initial grid location. If the absolute difference between the wind sea direction (at the upwind point) and the wind direction is less than 90 deg, the peak wave number at the upwind grid point is used in the wave growth calculations. If the upwind wave and wind direction differ by more than 90 deg, a new wind sea is commenced at the initial location with default parameters linked to a peak frequency of 0.5 Hz. Future research into model improvements will be directed toward a more physical source term calculation such as that of Hasselmann and Hasselmann (1985b).

18. The rapid wind shift modification will also enhance modeling near sharp, synoptic weather frontal systems. It should also be recognized that in most wave hindcast simulations, the rate of change of wind direction is much slower than hurricane or frontal passage simulations. In many such cases advection of wave energy will be from an upwind direction because the wind has already changed at these locations, and a definable fetch length will have developed.

19. One final adjustment has been made to the model that is not directly related to the hurricane problem, the addition of a swell dissipation sink term. A survey of the literature suggests several forms for this function (Resio 1981, Hasselmann and Hasselmann 1985a, and Hasselmann et al. 1985). From the variation in equational forms, it was clear that there was not a uniform understanding of dissipation. The various source functions were compared. The form selected for use is from Hasselmann et al. (1985) given by

$$S_{dis} = -\lambda \left(\frac{\omega}{\bar{\omega}}\right)^2 \hat{\alpha}^2 F(\omega,\theta)$$

$$\alpha = \varepsilon \omega^4 g^{-2}$$

$$\bar{\omega} = \varepsilon^{-1} \iint F(\omega,\theta)\ d\omega d\theta$$

$$\varepsilon = \iint F(\omega,\theta)\ d\omega d\theta$$

This form has a slightly greater rate of dissipation than that of Hasselmann et al. (1985) and is computationally stable. This source function is applied only for the swell spectrum and is effective only if the swell is very steep.

PART IV: MODEL VERIFICATION

20. Verification of a numerical model such as SHALWV is difficult because there are no analytical tests or solutions that can be applied to prove that the model is correct. There are two reasonable approaches to testing the model's reliability. The first approach is to compare model results to measured data. The second approach is to test the model with a series of controlled fetch-limited and duration-limited wave growth tests.

21. When comparing simulated results with observed data, there are many potential sources of error. They are:

- a. The representation of bathymetry may be too coarse or incorrect.
- b. The wind speed and directions are unlikely to be perfectly represented over a large spatial area and a long period of time.
- c. There are gage biases and errors as well as random sampling errors.

The confidence bands on most gage observations are relatively large, and there are very few sets of directional data available. For any type of wave conditions there are only limited sets of data with both offshore and nearshore directional wave measurements. Very often when model predictions are different from observations, it is possible to explain the differences by reasonable errors in the wind estimates. Given these many sources of uncertainty, it can only be expected that gross errors will be found in a wave model.

22. The foregoing statements represent a stringent assessment of the state of the art of wave modeling and should not be taken too pessimistically. The paragraph implies that most state-of-the-art wave models are predicting the gross parameters of the sea surface with an uncertainty that is comparable to the general error level of input variables to the model. It is unreasonable to expect a model that could compensate for the level of input error and always produce output of higher quality. At the present state of the art, it is possible to predict wave conditions down to the level of the directional spectrum practically anywhere that wind information can be estimated within reasonable accuracy. Wave characteristics may be estimated on a grid mesh small enough to represent variations in the wave field because of bathymetric changes that would not be generally economically feasible to acquire through measurements. That wave estimates can be made for conditions where gages have failed or for which gage data are unavailable does not in any sense indicate

that wave models are perfect. It simply requires that better sets of field data are needed to show where improvements must be made. Cardone's (1986) assessment is that where high quality wind data are available, the level of error in height, period, or direction is of the order of 10 percent. However, it is certainly possible to do far worse if the weather information is of poor quality. Therefore, the following goals were set for the validation of SHALWV:

a. For deep water the model should reproduce the Joint North Sea Wave Program (JONSWAP) (Hasselmann et al. 1973) growth curves for height and peak period.

b. For shoaling on a plane beach, the transformation of the mean angle with decreasing depth should approximate the linear monochromatic wave refraction.

c. For real simulations there should be no bias in predictions of height, period, or direction. The prediction of spectral shape should be consistent with observations when both the period and height are accurately predicted.

PART V: IDEALIZED SIMULATIONS

Nondimensional Growth Rate Tests

23. It is always constructive to return to sets of standardized tests to determine if internal modifications to any wave model will affect previous results. The tests were selected from initial SWAMP (The SWAMP Group 1985) experiments, and the SHALWV results were compared primarily to the Exact-Nonlinear computations by Hasselmann and Hasselmann (1985a). The range of other model results is also indicated in all diagrams.

24. Figures 2-5 provide plots of dimensionless energy and peak frequency against dimensionless fetch and duration for the model versus the JONSWAP experimental values and the Exact-Nonlinear model of Hasselmann and Hasselmann (1985a). For SHALWV, a stationary, uniform wind field with a velocity of U_{10} = 20 m/sec (10 m in elevation wind speed) blows in an offshore direction. A second test was run at a wind speed of 30 m/sec. The water depth was set to 2,000 m at all grid locations. The initial wave energy was set to zero. The wave models were run until a steady-state condition was reached within the entire region providing the necessary information to describe fetch-limited wave growth in deep water. The test case also yields duration-limited wave growth curves from the time evolution at large distances from the coast.

25. A friction velocity was used as the nondimensionalizing velocity scale factor. Although this scaling factor was commonly used, many differences were found in comparisons between various SWAMP model results (The SWAMP Group 1985). There is usually an uncertainty whether the frictional velocity or the wind velocity or other boundary layer parameters control the simulated rate of growth. This effect is amplified by the uncertainties associated with the specification of the drag coefficient relating the frictional velocity to the 10-m wind speed.

26. The JONSWAP results for fetch-limited conditions were obtained primarily from field data (Hasselmann et al. 1973). These curves have been widely accepted in the scientific and engineering community to determine energy and peak frequencies over a wide range of input conditions. For the nondimensional energy, SHALWV results fall within the JONSWAP ±5 percent range (Figure 2) whereas SHALWV's nondimensional frequency results (Figure 3) tend

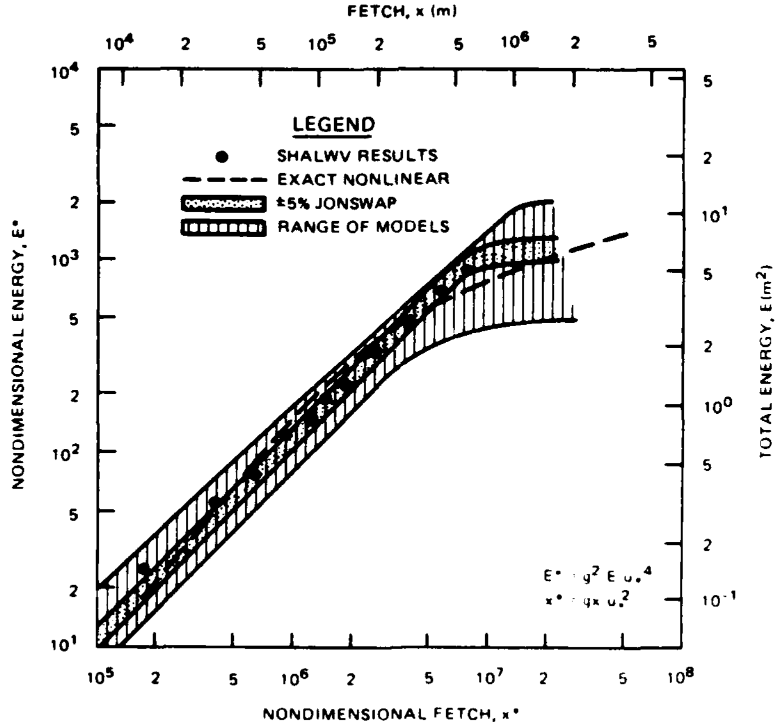


Figure 2. Growth rate with fetch and nondimensional energy E* versus nondimensional fetch x* (dimensional fetch length and total energy obtained from frictional velocities)

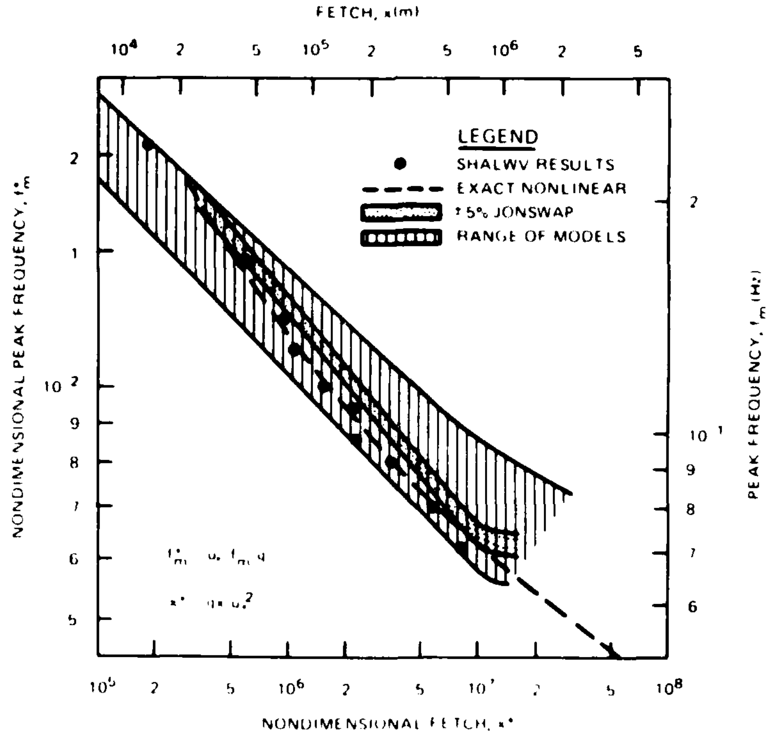


Figure 3. Growth rate with fetch and nondimensional peak frequency f^*_m versus nondimensional fetch x* (dimensional fetch length and peak frequency obtained from frictional velocities)

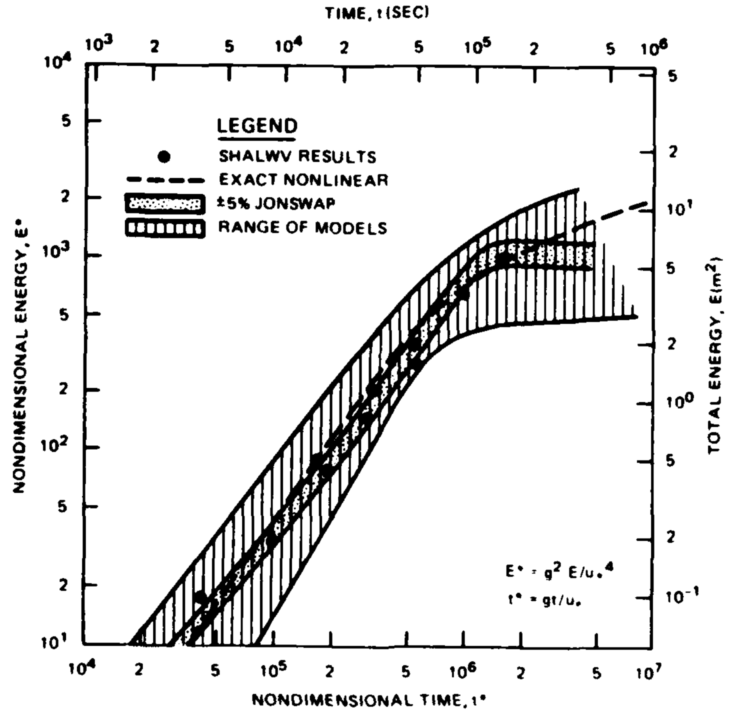


Figure 4. Growth rate with time and nondimensional energy E* versus nondimensional time t* (dimensional time and total energy obtained from frictional velocities)

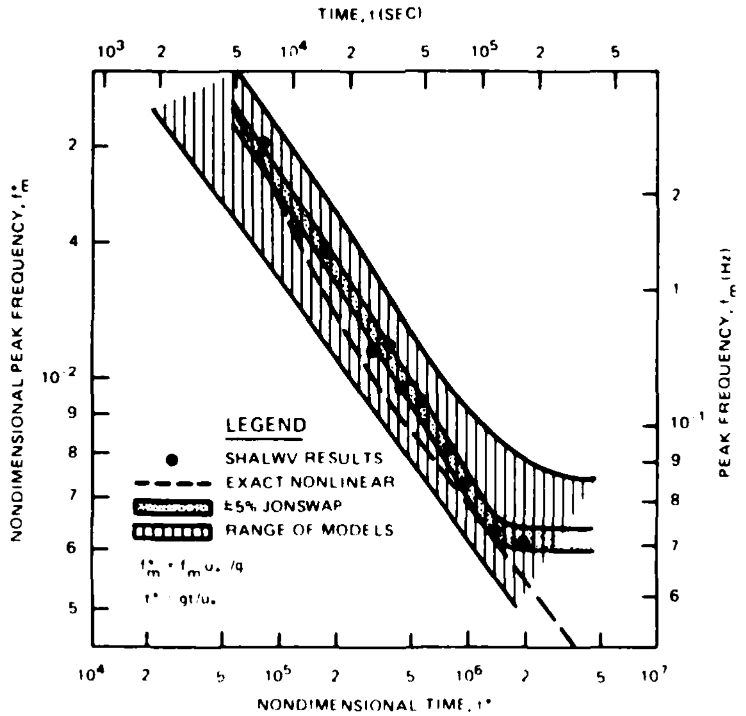


Figure 5. Growth rate with time and nondimensional peak frequency f^*_m versus nondimensional time t* (dimensional time and peak frequency obtained from frictional velocities

to be slightly lower but closer to the Exact-Nonlinear model result.

27. No universally accepted set of duration-limited field data exists, so the Exact-Nonlinear model calculations were used as a basis of comparison. As shown in Figure 4, SHALWV nondimensional energy estimates are scattered about the Exact-Nonlinear results. In Figure 5, the nondimensional frequency obtained from SHALWV tends to be slightly greater than that in the Exact-Nonlinear results. The divergence from the Exact-Nonlinear curve at t^* greater than 2×10^6 is attributed to limitations placed on f_m (peak frequency) in SHALWV to force a fully developed spectrum that had not been added into the Exact-Nonlinear computations.

28. Overall, SHALWV results were within ±10 percent of the target curves. Since the target data were either empirical or based on simulation, no attempt was made to force closer agreement.

Plane Beach Refraction Tests

29. Traditionally, the primary conservative processes considered in nearshore wave transformation have been refraction and shoaling. Numerous models have been developed to treat these processes similar to the principles of geometric optics. These processes can be applied to spectral wave modeling. Refraction and shoaling do not force a spectrum toward a consistent spectral shape. Rather, they tend to introduce variations in the spectral shape related to directional distributions of wave energy or local bathymetric effects. For this test, we are only considering the variation in changes in the mean direction of the 2-D spectrum compared to a linear, monochromatic theory approach.

30. Figure 6 is a plot of the mean angle from SHALWV versus distance from shore. The computations were initiated at a water depth of 100 m, and the 2-D spectrum was propagated over a bottom slope of 1:1,000. A TMA spectrum (Hughes 1984) was established with peak frequency of 0.1 Hz. A similar monochromatic, unidirectional wave was transformed via standardized techniques (SPM 1984) and the results plotted. Estimates from SHALWV display similar trends common to the linear theory approach. The directional spread and energy transfers from low to high frequencies found in SHALWV tend to slightly slow the rate at which the mean wave direction approaches shore-normal as shown in Figure 6.

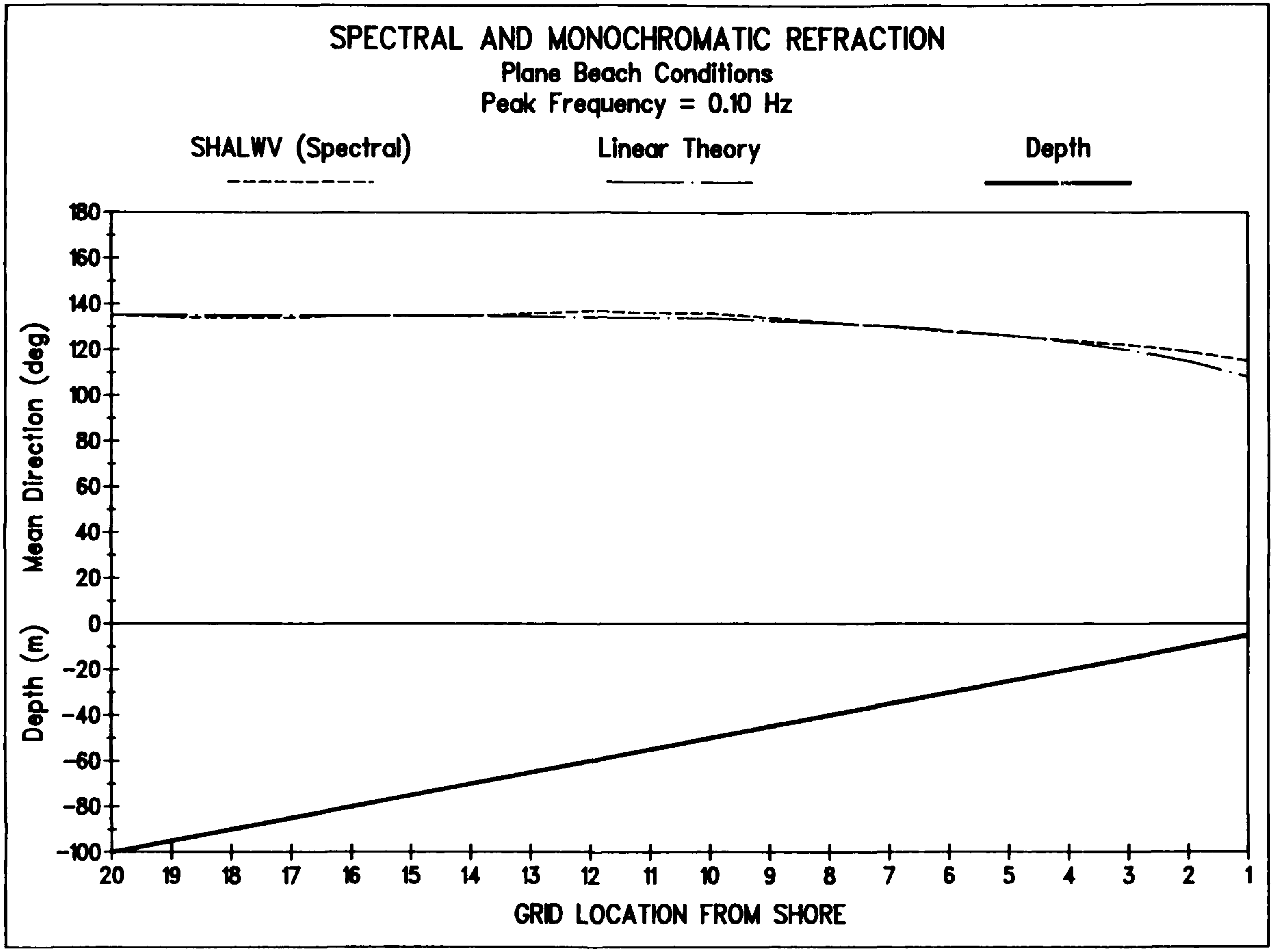


Figure 6. Spectral and monochromatic wave refraction over plane beach comparison

PART VI: STORM SIMULATIONS

31. Five storm simulations were performed to verify SHALWV's results. Additionally, two unique extratropical storm sequences--the Atlantic Remote Sensing Land Ocean Experiment (ARSLOE) and the January 1983 Pacific Ocean storm--were selected because of their unusual behavior. ARSLOE was characterized by its rapidly turning winds and the January 1983 Pacific Ocean storm by its intensity and damaging effect on coastal structures. Wave data in both storm sequences were gathered at many sites resulting in a large amount of high quality wave data for comparisons.

32. Three hurricane storms--Camille, Edith, and Gloria--were simulated. Because of the cooperation of many oil corporations in the mid-1960's, wave data were obtained for many of the Gulf of Mexico hurricanes. During the fall of 1985, a large-scale field experiment at the Coastal Engineering Research Center's Field Research Facility (FRF) near Duck, North Carolina, was nearing completion when Hurricane Gloria began its northerly track passing near the FRF's wave gaging operations.

33. Hence, the five storms displayed unique characteristics; and, because of gaging activities, the wave data could be used for extensive verification over a wide range of wind fields and water depths.

ARSLOE Field Case

34. During the ARSLOE field experiment (Baer and Vincent 1983) an array of gages collected data during a typical fall storm near Duck on 25 October 1980. The ARSLOE data set shows, interestingly enough, an example of a comprehensive data set providing not only a good base for model comparison but also the complexity of a seemingly simple storm simulation. The gage locations, bathymetry, and grid are shown in Figure 7. The model simulation was made using a 3-km grid with data input on the outer boundary from the Experimental Environmental Research Buoy (XERB), a directional wave buoy. The frequency spectrum and mean direction at XERB were input along the entire offshore boundary. Lateral boundary information, dependent on variations in the water depth, was estimated by a fully spectral wave transformation routine written by Dr. R. E. Jensen (adapted from Jensen (1983) and specifically

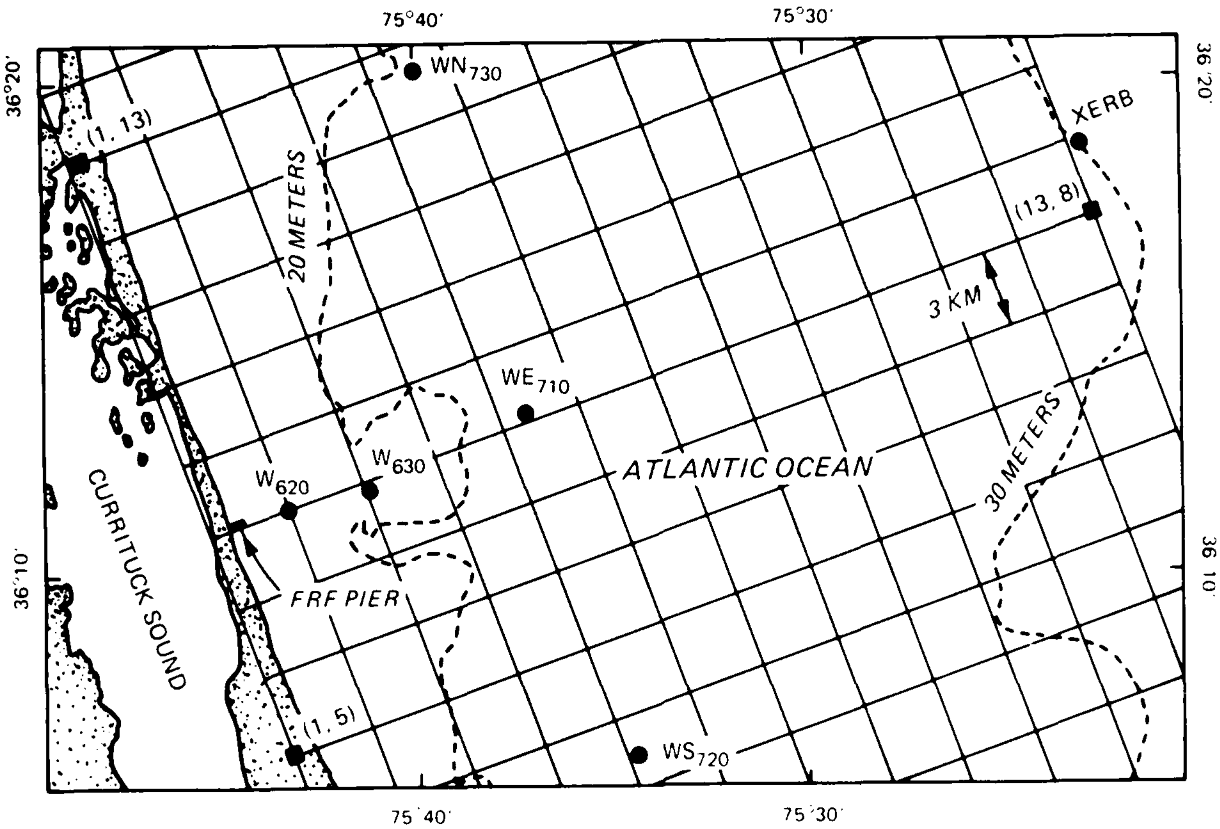


Figure 7. ARSLOE location map

written for SHALWV).* The wind field over the grid was assumed to be uniform in speed and direction and obtained from XERB (Figure 8).

35. The simulated ARSLOE storm included an easterly directed frontal passage (from shore to the offshore boundary) which caused a decided shift in the wind that took place 1 hr earlier onshore than offshore. Consequently, there is an inhomogeneity in the wind field over the limited 42- by 36-km region simulated during an important part of the storm. ARSLOE provided the necessary factors to test the rapidly turning wind algorithm developed for SHALWV.

36. Hindcast results at the northern and southern gages were partially influenced by the side boundary conditions transformed directly from the XERB wave data. The spectral transformation routine employed is not of the level of sophistication for wave growth and nonlinear interactions found in SHALWV, but it does provide a way to restrict energy leakage at the boundaries for

* This computer algorithm and user's manual will be made available in the future.

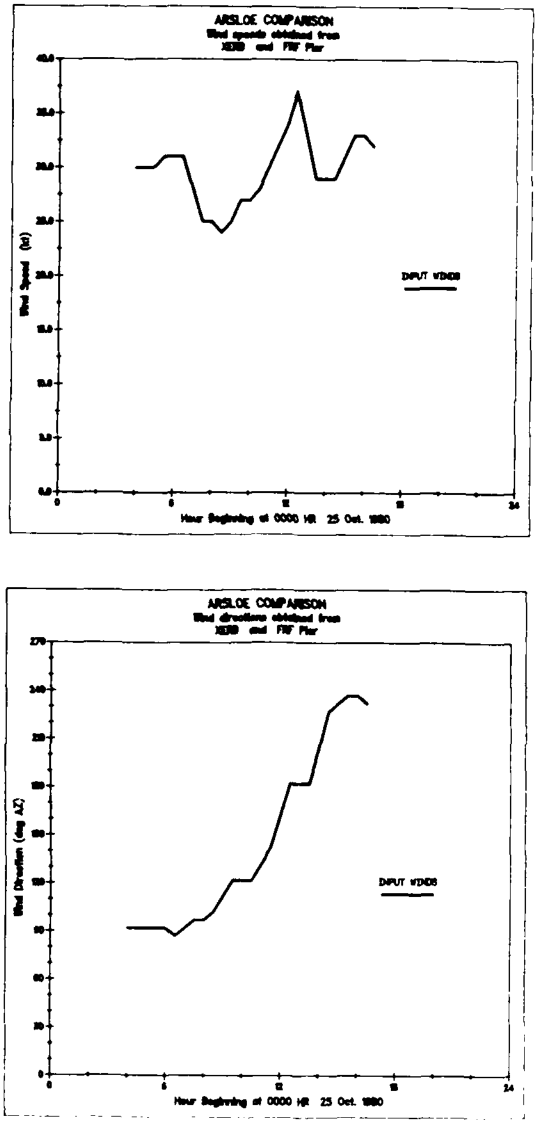


Figure 8. ARSLOE input wind speed and direction data

open coastal areas while limiting contamination of the wave characteristics in the grid system. Figure 9 is a plot of the energy based wave heights H_{mo} at XERB and at gages on the interior of the grid. All show a pattern of a rise from about 3 m with maximum wave heights between 4 and 4.5 m. The gages to the east and south of the pier (Gages 710 and 720) display multiple peaks of approximately the same magnitude in the storm. XERB and the northernmost gage do not show these phenomena, nor is there any indication that the wind field

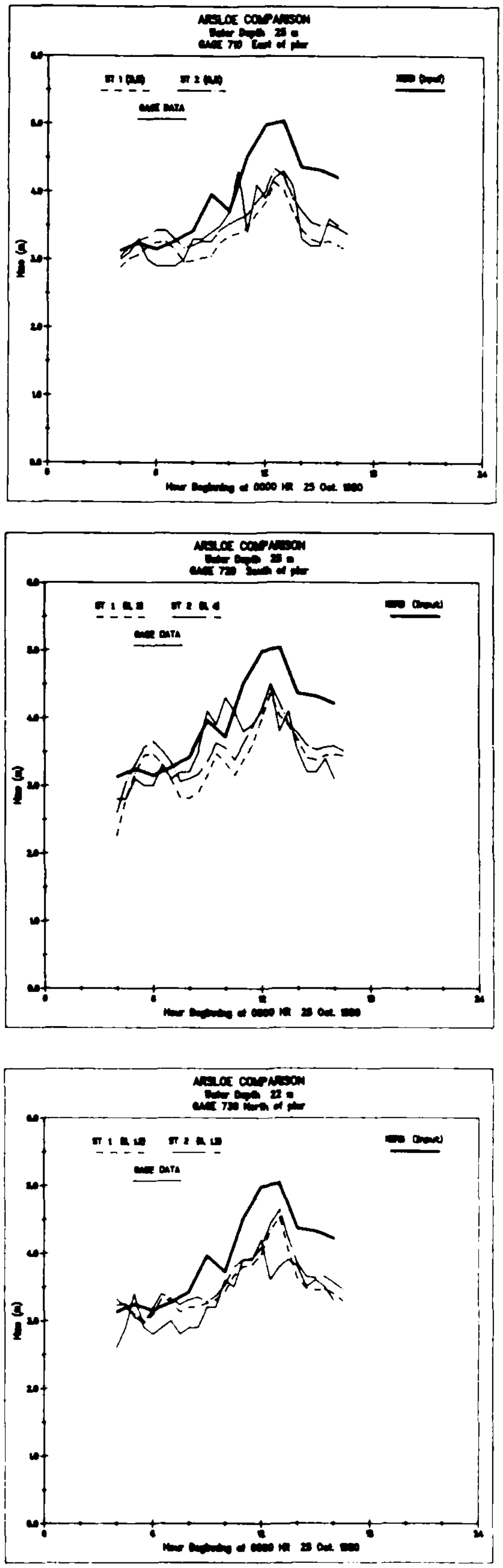


Figure 9. Wave height comparisons versus time for gages 710, 720, and 730 (simulated results derived from two adjacent grid locations near gage site; all plots with deepwater boundary conditions from XERB)

would cause these double peaks in the wave field. Since neither the driving boundary condition (XERB) nor the input wind shows a double peak, it is not surprising that the model does not show a secondary peak. Thus, there appears to be a secondary swell train that only affects the southern half of the grid. Overall, SHALWV results depict the general rise and fall of the storm found in the gage data. The two new additions to SHALWV (rapidly turning winds and swell dissipation) effectively remove energy during the latter portion of the storm. For all three locations the simulated decay rates (Figure 9) are nearly identical to the measured results.

37. Peak spectral wave periods T_p were compared for the same time period at all three gage locations (Figure 10). The complex nature of this particular storm is shown more clearly in these results. For the initial two-thirds of the storm (0400-1300 EST), the coastal area was under the influence of local wind sea conditions (T_p values from 8 to 9 sec). As the wind direction shifted to an offshore direction, the wave climate changed dramatically and became dominated by swell wave conditions (T_p values near 12 sec). Typically, the SHALWV results follow the trends of the gage results.

38. Energy based wave height H_{mo} comparisons were made also with respect to wave gages in slightly less shallow water (Figure 11). The measurements show a maximum H_{mo} at nearly the identical time as Gages 710 and 720. Unfortunately, at the assumed maximum of the storm (1200 to 1300 EST), both sets of gage data were missing. Visual observations indicate that wave data at the end of the FRF pier did not exceed 3.6 m. The SHALWV wave height results show trends similar to those in the measurements, although the first maximum is underestimated. Since the simulated H_{mo} was derived from XERB (both gages recorded higher wave conditions than XERB during the hindcast), the differences do not appear to be significant.

39. Two final types of comparisons were made between SHALWV and the gage results: frequency spectra and directional comparisons to a series of directional measurements (four types of devices) seaward of the FRF pier. The spectra were obtained from maximum H_{mo} conditions during the storm sequence. Figure 12 displays those comparisons at the three centrally located gages (Gages 710, 630, and 620). When the confidence bands associated with the measured data are considered, SHALWV spectral results are very reasonable, considering the model was driven with a measured spectrum from one point (XERB) located 36 km offshore (the grid resolution of 3 km) and assuming the wind

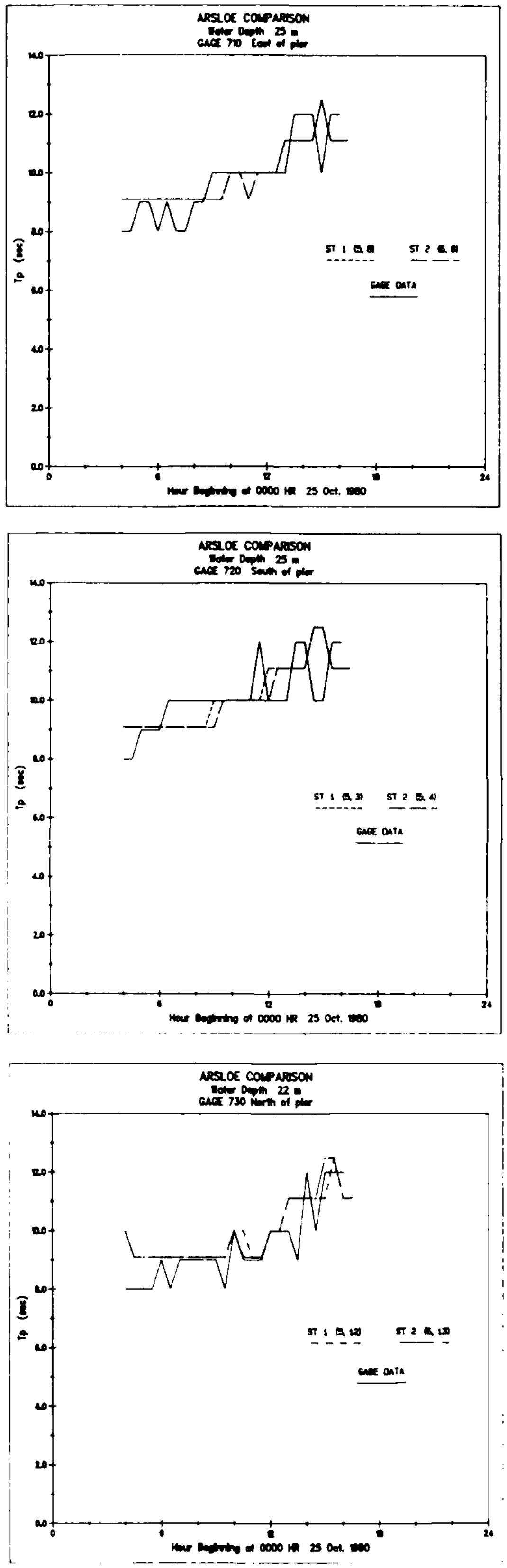
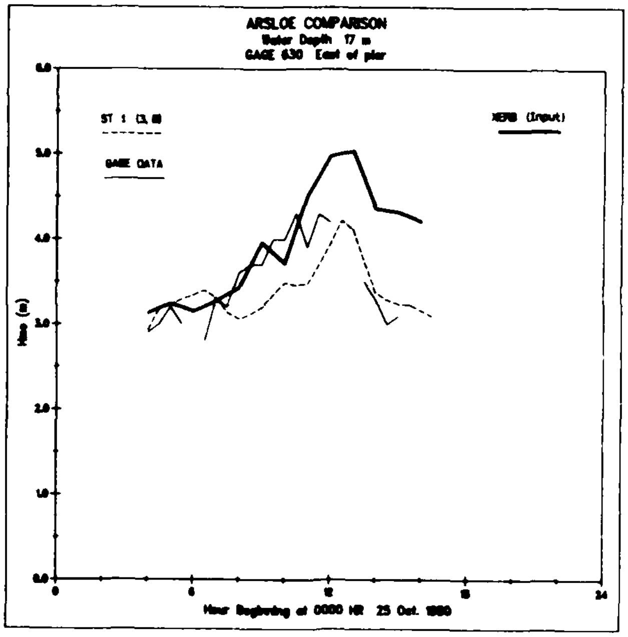


Figure 10. Comparison of peak spectral wave periods with time at Gages 710, 720, and 730



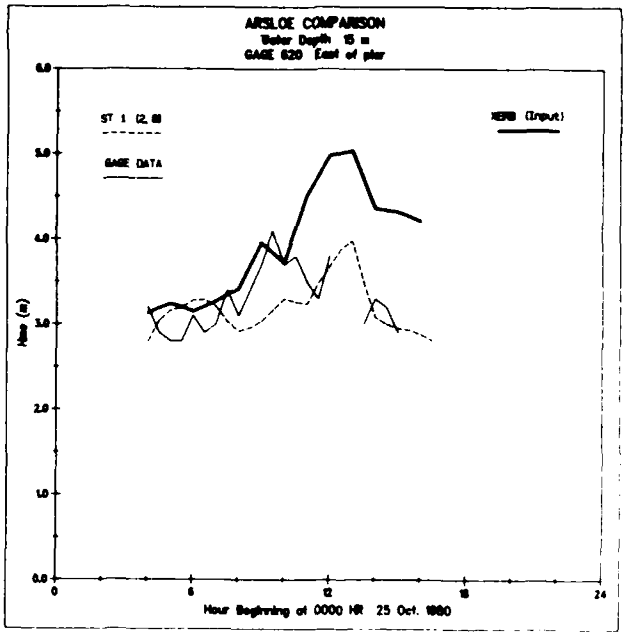


Figure 11. Wave height comparisons versus time for Gages 630 and 620 (deepwater boundary condition trace identified by XERB)

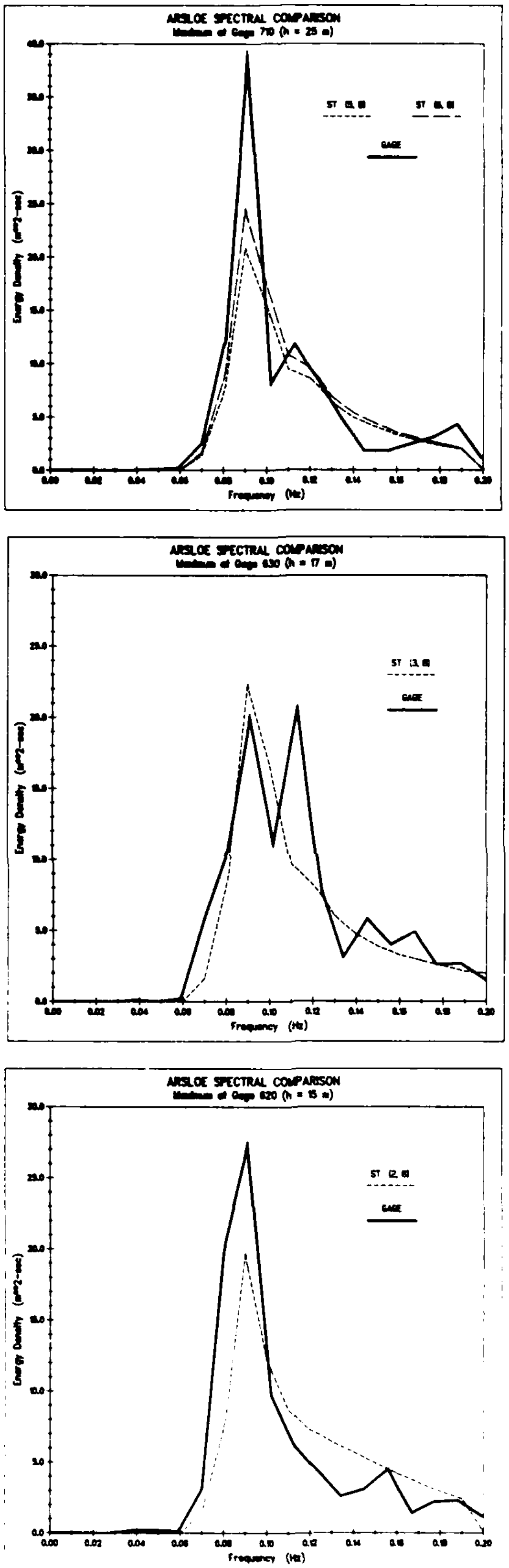


Figure 12. 1-D frequency spectral comparisons for maximum wave height conditions during the ARSLOE storm sequence east of FRF at Gages 710, 630, and 620 in three different water depths

field was uniform over the study area. Figure 13 shows the simulated results plotted against the range of the gage estimates for the mean direction. For all cases SHALWV results fall within 10 deg of the midpoint of the range.

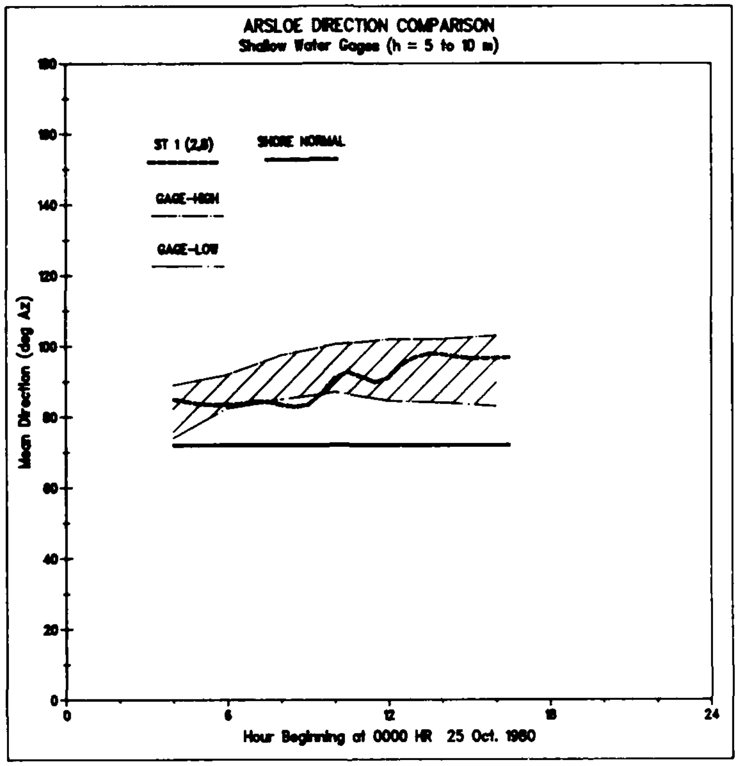


Figure 13. Mean wave direction comparisons in shallow water (range of measured data sets shown by hatched lines; shore-normal wave conditions 72 deg)

Hurricane Camille

40. Hurricane Camille in 1969 was one of the most severe hurricanes to hit the Gulf of Mexico in this century. Wave data were gathered at a series of oil rigs off the Louisiana coast (Figure 14) by the Ocean Data Gathering Program (ODGP) (Hamilton and Steere 1969) sponsored by a consortium of oil companies. ODGP gage locations are shown in Figure 14 as ODGP 1-6 and are used in comparisons.

41. Since the original report's release, other authors have reanalyzed the raw data sets, generating new spectral and H_{mo} estimates. We have restricted our verification of SHALWV to four unique data sets:

a. Patterson (1974).

b. Reece and Cardone (1982).

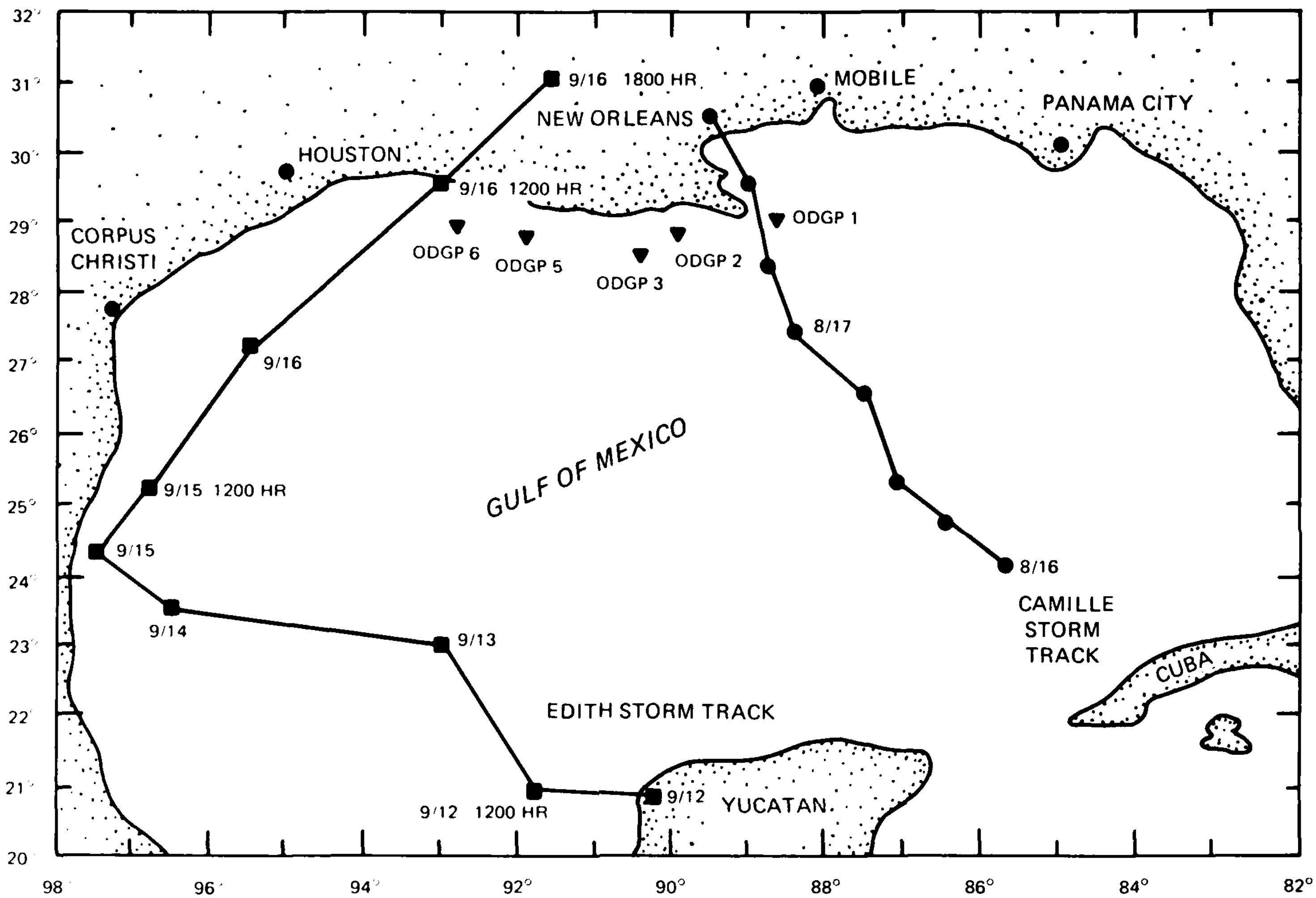


Figure 14. Hurricanes Camille and Edith storm tracks in the Gulf of Mexico

c. Hamilton and Steere (1969), ODGP.

d. Grosskopf et al. (1984), reanalysis of ODGP.

42. The hurricane was simulated on a two-grid system (Figure 15). The first was a 30-nautical mile grid covering most of the Gulf of Mexico; the second was a finer 15-nautical mile grid covering the coastal region near the landfall point of the hurricane. The wind fields were calculated by utilizing the PBLM for both grids. Computations were made at a 30-nautical mile scale and saved for input to 15-nautical mile scale.

43. Camille was a very heavily studied storm, and the wind conditions have been analyzed to a high degree. The storm was well behaved (i.e., the wind fields simulated by the PBLM can more readily describe the actual event). Comparisons between observed and predicted wave height for the three stations are in good agreement considering how the maximum measured wave height varies from one analysis procedure to the next, and the predicted wave heights are estimated from grid points surrounding the actual gage location (Figure 16). Bottom topographic features arising from the deltaic structure give rise to strong gradients in water depth at ODGP 2 and 3. Approximating these features on a 15-nautical mile grid is very crude, but as shown in the comparisons, it is not particularly critical. Also, during the most intense portion of the hurricane, the wind sea and swell components propagate nearly parallel to the bottom contours in the region around ODGP 2 and 3. It is important to note that SHALWV predicted the wave climate very well considering such complex conditions. Since ODGP 1 was close to the eye and ODGP 2 and 3 were to the left of the eye, the good agreement suggests that the model is producing a reasonable pattern of outflowing swell from the storm center.

44. Comparisons were made also between observed and predicted frequency spectra for maximum conditions at the three ODGP locations (Figure 17). Measured spectra from Grosskopf et al. (1984) were selected as the basis for comparison to the SHALWV results. The simulated results were in good agreement at all three locations, considering the confidence limits associated with the measured results.

Hurricane Edith

45. Hurricane Edith, which occurred September 1971, is a less well understood storm than Camille. On 13 and 14 September, the storm crossed the

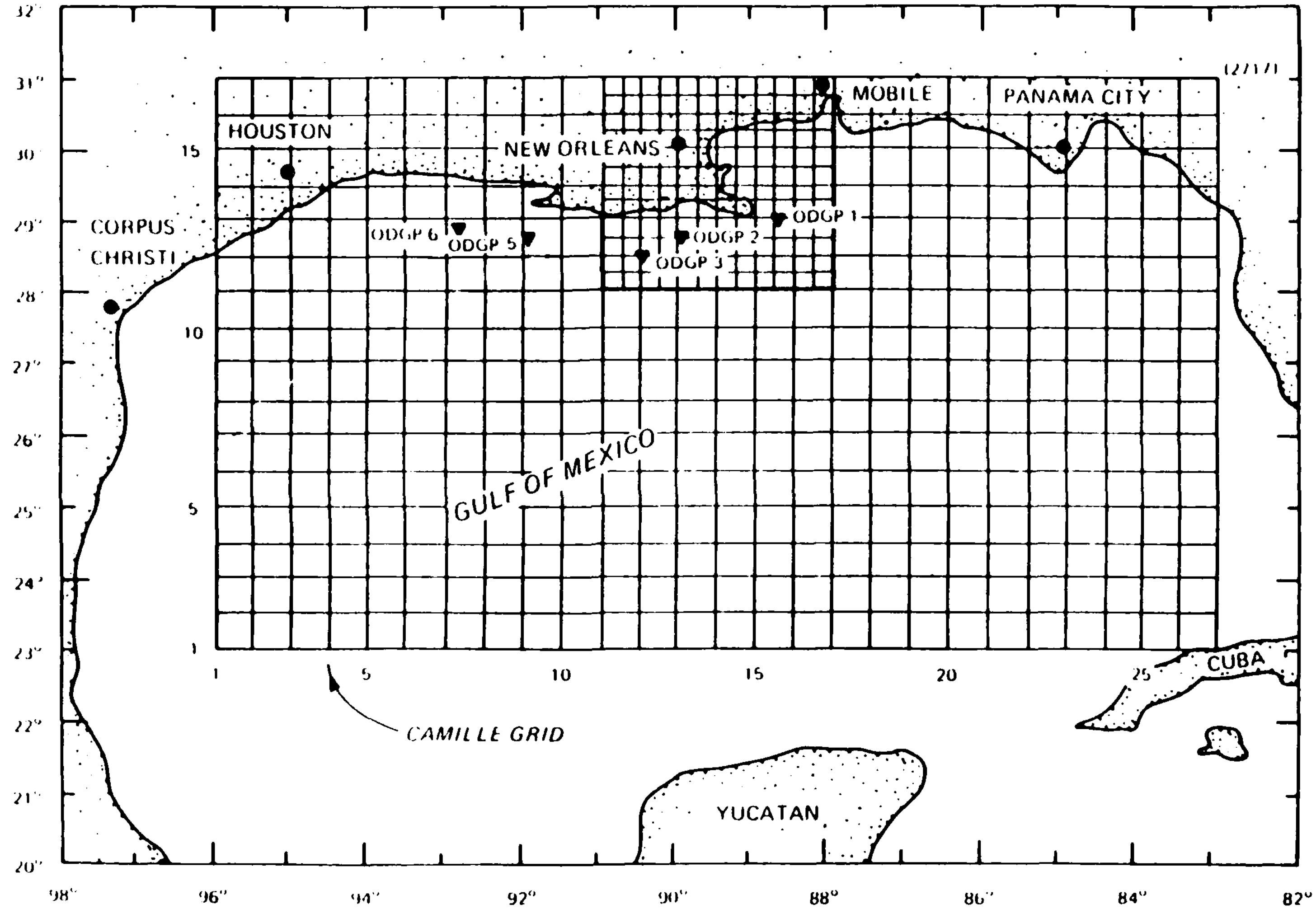


Figure 15. The 30- and 15-nautical mile SHALWV grids used for the Hurricane Camille simulation

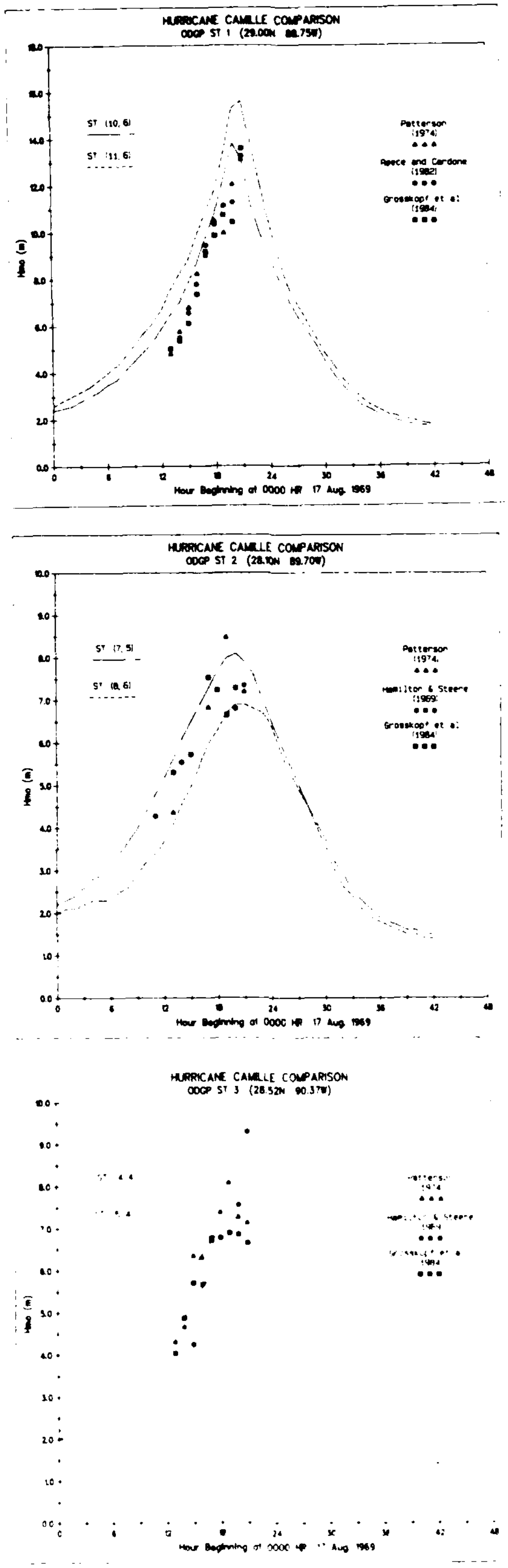


Figure 16. Wave height versus time comparisons for Hurricane Camille at ODGP 1, 2, and 3 (simulated results represented by grid locations closest to gages)

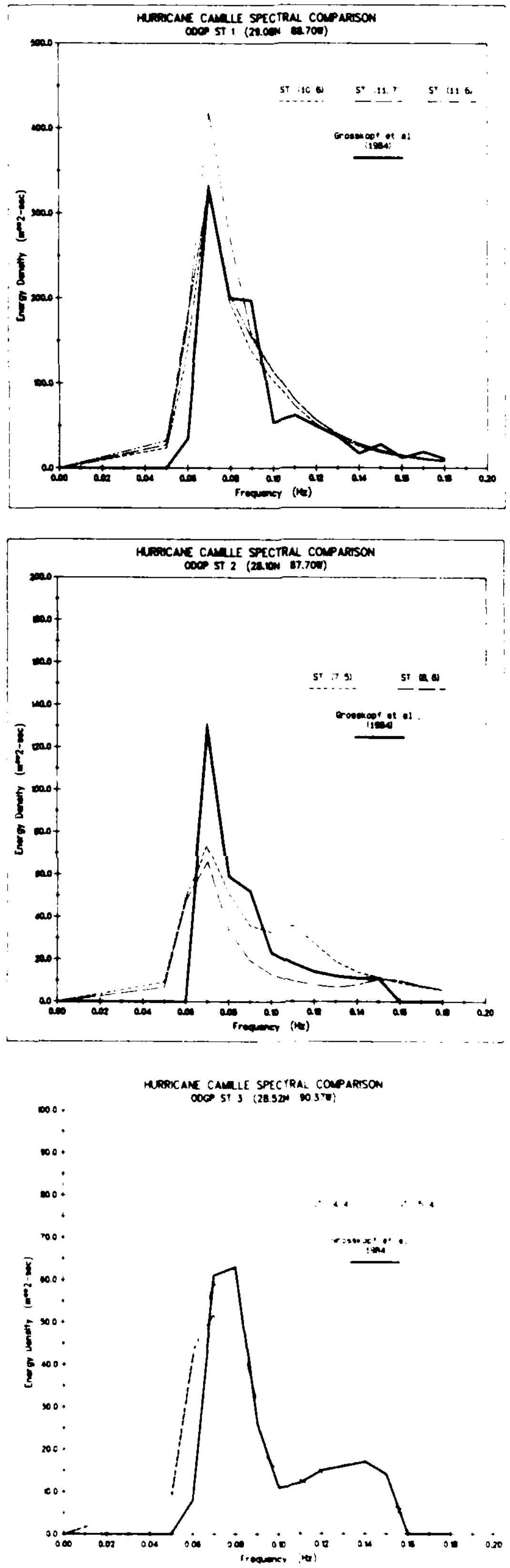


Figure 17. 1-D frequency spectral comparisons for maximum wave height conditions during Hurricane Camille at ODGP 1, 2, and 3

Gulf of Mexico from Yucatan to the Rio Grande as a tropical storm and looked as if it would go ashore in Mexico on 14 September (Figure 14). On 15 September, Edith turned more than 90 deg and moved parallel to the Texas coast, intensifying to hurricane strength and crossing the shore into West Louisiana. The storm was captured on ODGP 1 through 6, with the most severe conditions occurring near ODGP 6 (Hamilton 1972). This storm developed a front-like squall band that moved down the Louisiana coast producing high waves at ODGP 1 through 4. The squall band could not be predicted in the PBLM, so only the data from ODGP 5 and 6 near the storm center will be presented.

46. Comparisons of the model and gage observations show general agreement in energy based wave height (Figure 18). The peak height at ODGP 6 is underestimated by approximately 12 percent, while at earlier times the model wave heights at this gage were slightly higher than observed. The comparison of wind observation and prediction at this site shows a similar pattern, and it is likely that an underestimation of the peak wind may have accounted for this difference. During the maximum wave height, the estimated peak period was about one second longer than the measured. Hence, comparisons between spectral estimates were not made.

Hurricane Gloria

47. Gloria was a severe Atlantic coast hurricane in September 1985. Data were available at a data buoy off South Carolina near the path of the storm near its most intense phase and at the FRF (Figure 19). The hindcast presented here is based on early data reconnaissance from the storm (Coastal Engineering Research Center, Field Research Facility 1985 and Lawrence 1985).* Since the storm had anomalous structure (at one point the region of maximum wind was reported about 100 nautical miles wide), a more detailed analysis should be undertaken of the storm meteorology, and the wave hindcasts presented here are considered a first attempt.

48. The grid was a 30-nautical mile grid extending from Maryland south to the Bahamas and 360 nautical miles offshore of Cape Hatteras. A 15-nautical mile grid was used in the vicinity of Cape Hatteras to Virginia Beach. Wave

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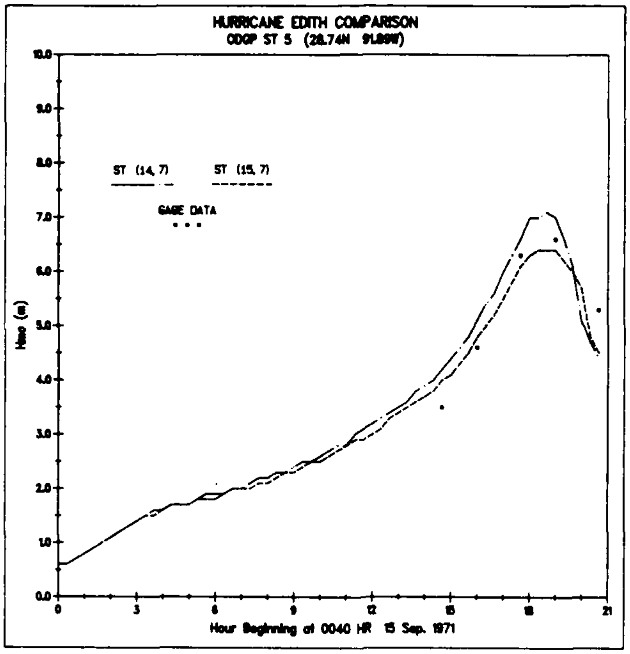
* Additional information was obtained through personal communication with H. Carl Miller and K. K. Hathaway at the FRF in April 1986.



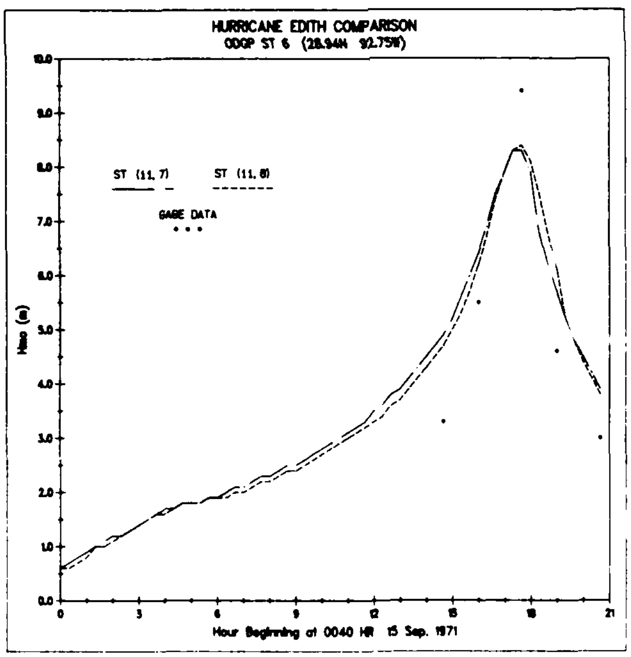


Figure 18. Wave height comparisons versus time during Hurricane Edith at ODGP 5 and 6

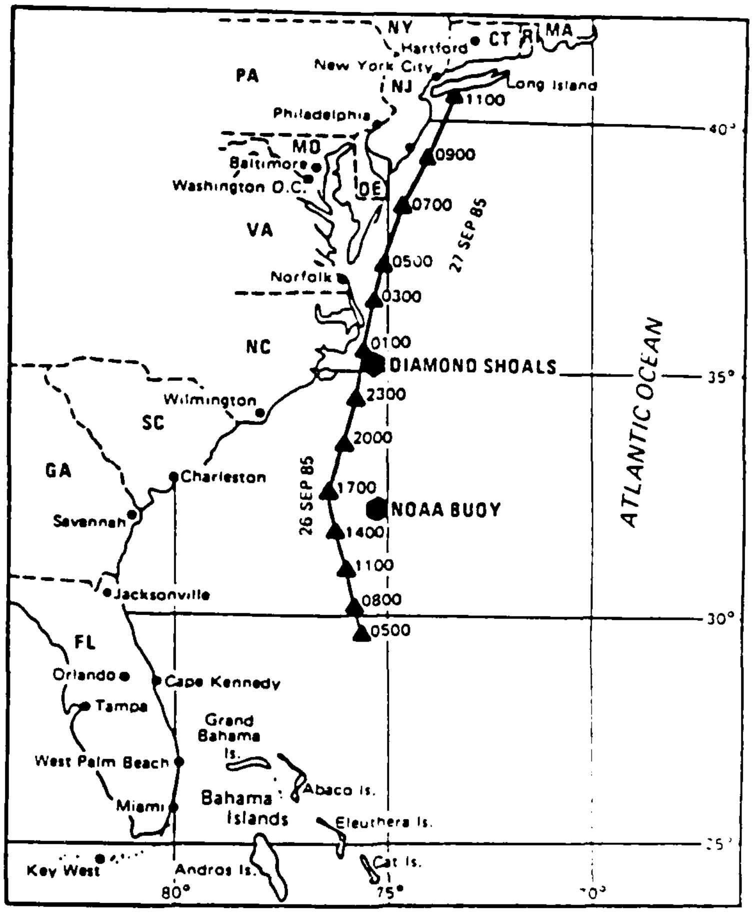


Figure 19. Approximate storm track for Hurricane Gloria (EST)

height predictions within 20 nautical miles of a National Oceanographic and Atmospheric Administration (NOAA) buoy offshore of South Carolina were 14.28 m with a 12.5-sec peak period. These values were almost identical to the observed values of H_{mo} = 14.3 m and T_p = 12.5 sec but occurred approximately 2 hr later than did the buoy maximum. Given the current degree of uncertainty about the storm wind field, these results may be better than should be expected.

49. At the FRF, the two closest grid points had estimated H_{mo} values of 6.0 m when a measured maximum of 6.9 m occurred (Figure 20). The Duck region was very close to eye passage. At grid locations approximately 15 nautical miles offshore in a similar depth of water (20 m), hindcast heights were over 7 m, while 15 nautical miles south they exceeded 8 m. Thus, small errors in placement of the storm as it passed this region could cause the discrepancies seen. Nearshore comparisons based on two directional gages in

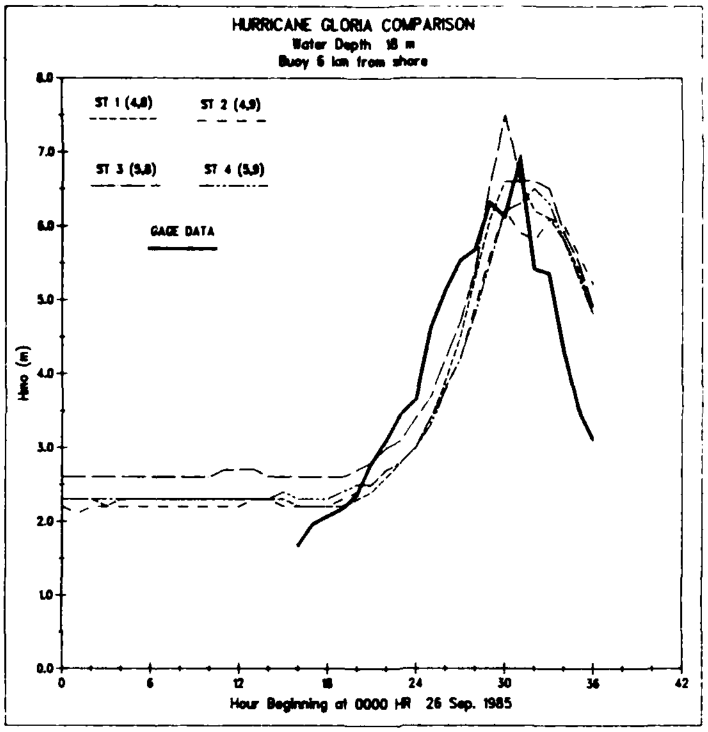


Figure 20. Wave height comparison versus time (EST) during Hurricane Gloria (four simulated result locations surround actual gage location)

approximately 6.5 m of water were made (Figure 21). There was an alignment error in the S_{xy} gage prior to the passage of the hurricane. Miller* suggested that this error was on the order of 30 deg. All results for the S_{xy} mean directions reflect an adjustment of 30 deg in the angle results. It can only be speculated why there is an extreme difference (40 deg) between the S_{xy} and P_{uv} results at 2100 EST.

50. Estimated wave conditions were generated from the fully spectral transformation algorithm (paragraph 34). Two simulations were made based on varying deeper water input conditions and displaying similar trends in the H_{mo} results. The simulated maximum results were approximately 0.3 m larger than the maxima found in the gage data. The directional information obtained from the simulation falls between the range of the two measured data sets. The most significant discrepancy in the Gloria hindcast was in wave period. The hindcast peak period was 12.5 sec in the Duck area. The wave observations show waves of predominantly 14 to 15 sec during the storm. The wave model

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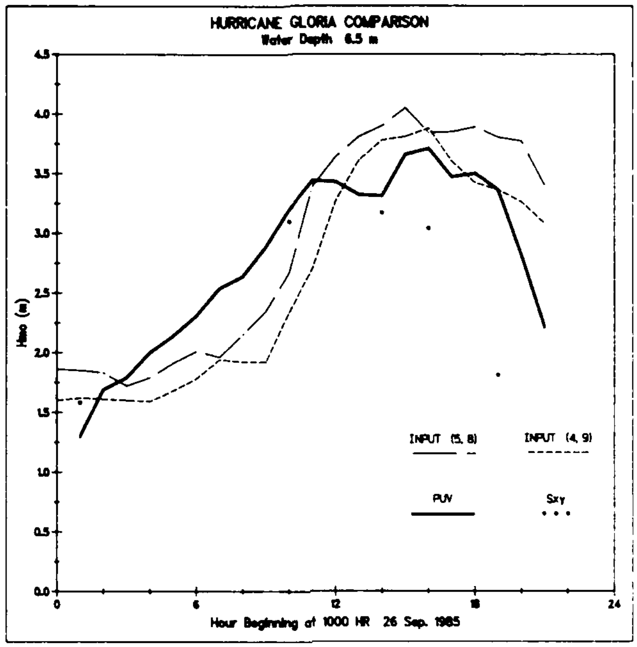
* See paragraph 47.



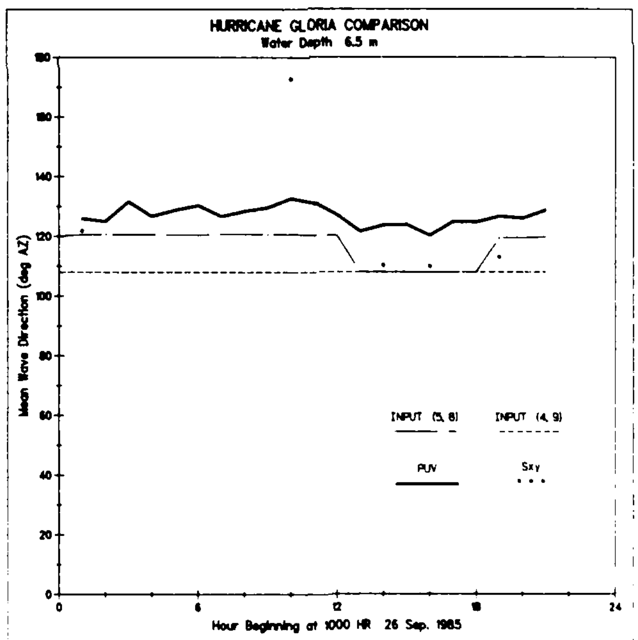


Figure 21. Wave height and accompanying mean direction comparisons versus time (EST) during Hurricane Gloria for shallow-water conditions

predicted a very large area of 14.3-sec peak periods, but this area was located more to the south and west of the Duck area. Thus, the model indicates that the storm produces 14-sec swell, though not in the Duck area. This problem may result from a poor description of the wind field, especially if the actual area of maximum winds was anomalously broad; however, its resolution can be found in a final wind field analysis of the hurricane.

Pacific Storm of January 1983

51. The final storm simulation to be discussed is an extremely large, energetic, extratropical storm system that was the first of many systems affecting the west coast of the United States during a 3-month period in 1983. A large storm off the California coast during 23 through 29 January 1983 produced some of the most severe wave conditions experienced in several decades in this area.

52. Several wave gages and buoys were in operation during some or all of this storm. The Coastal Data Information Program (CDIP) and the National Data Buoy Center (NDBC) deployed a total of four wave measuring buoys offshore of the San Francisco Bay area. The data obtained from these gages were derived from differing water depths and spatial locations that covered approximately 4,800 sq km. The Wave Information Study discrete spectral wave model (Resio 1981) had been previously used to hindcast the deepwater portion of this storm. Data from this handcast were used to drive a 5-nautical mile grid over the San Francisco Bay entrance area (Figure 22). The wind information was obtained from previous hindcast efforts and assumed to be constant in magnitude and direction over the entire grid.

53. Results were compared to those from gages in the region (Figures 23 and 24). The results indicate that SHALWV's predictions were in good agreement for initial growth, especially for the peak conditions and subsequent decay. The model predicts a longer time period of maximum wave heights, but this is a result of the 6-hr wind inputs to the larger deepwater model grid that drives SHALWV along the outer boundary.

Maximum Wave Estimates

54. Thus far, comparisons were concentrated on time-histories of heights and peak spectral periods as well as frequency spectra from measured

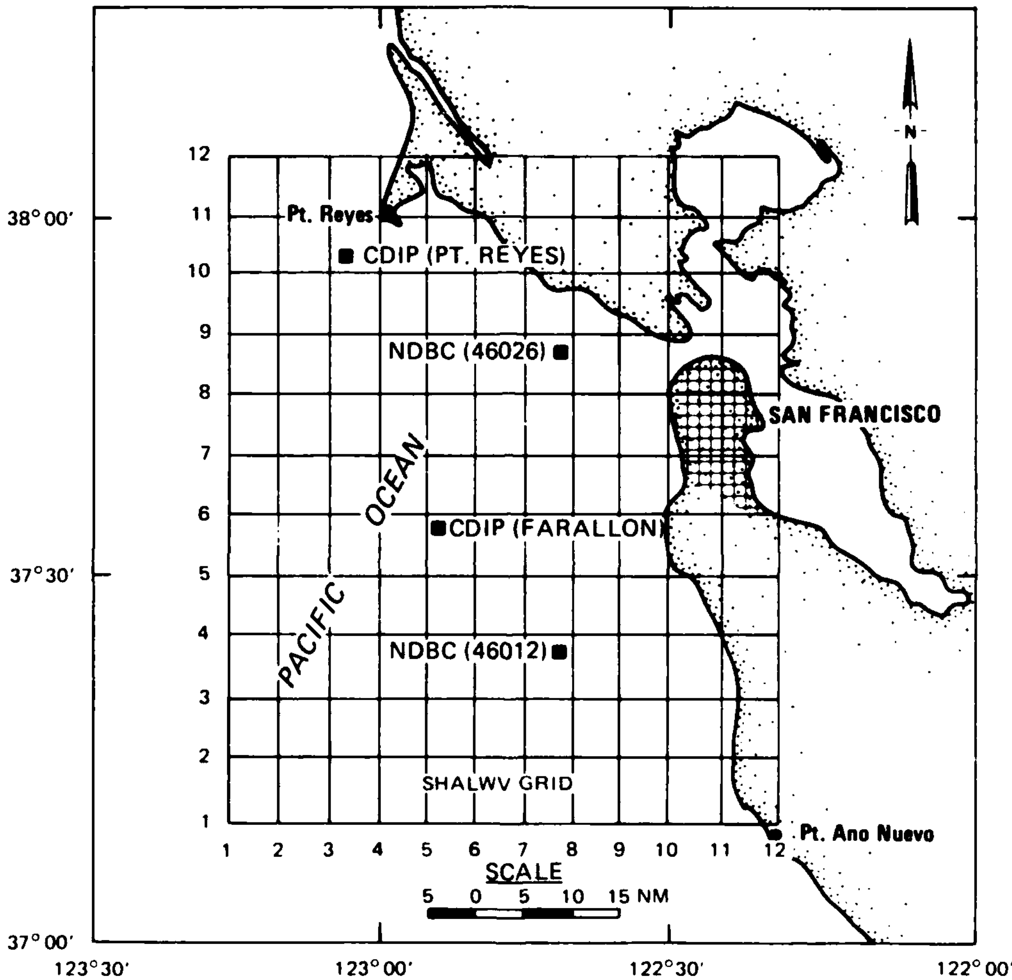


Figure 22. San Francisco area grid, with four gage locations, used for the Pacific storm of January 1983

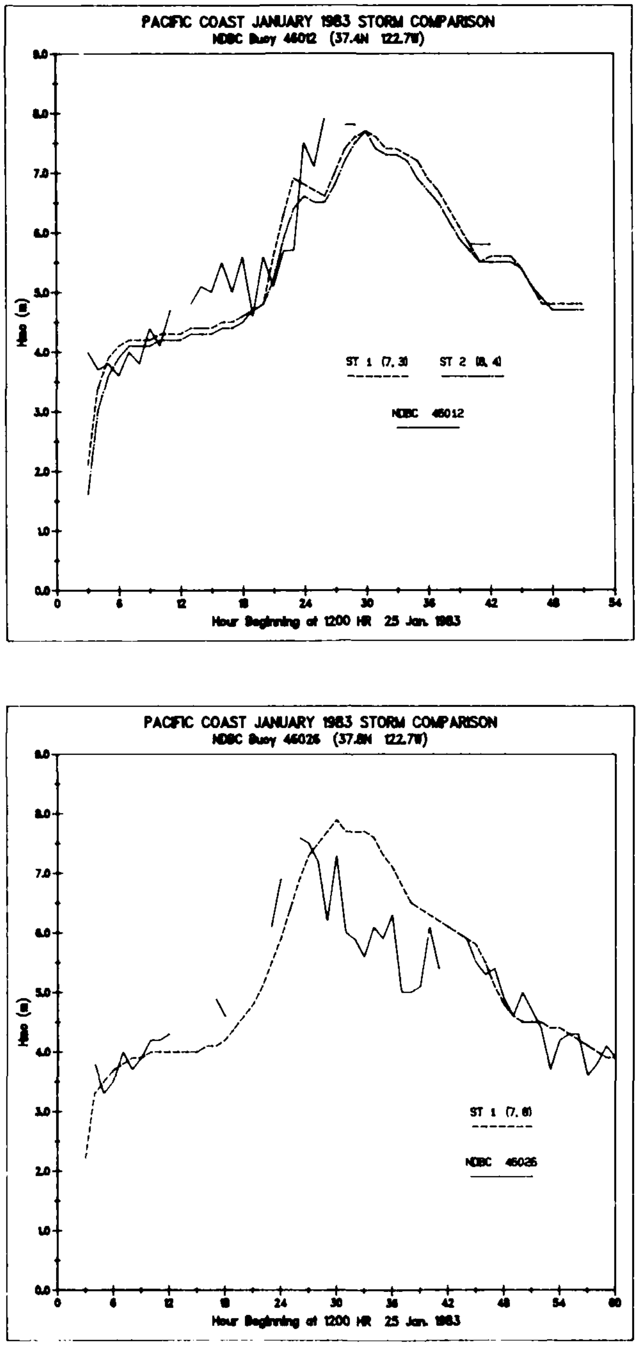


Figure 23. Wave height comparisons versus time at the two NDBC buoy locations

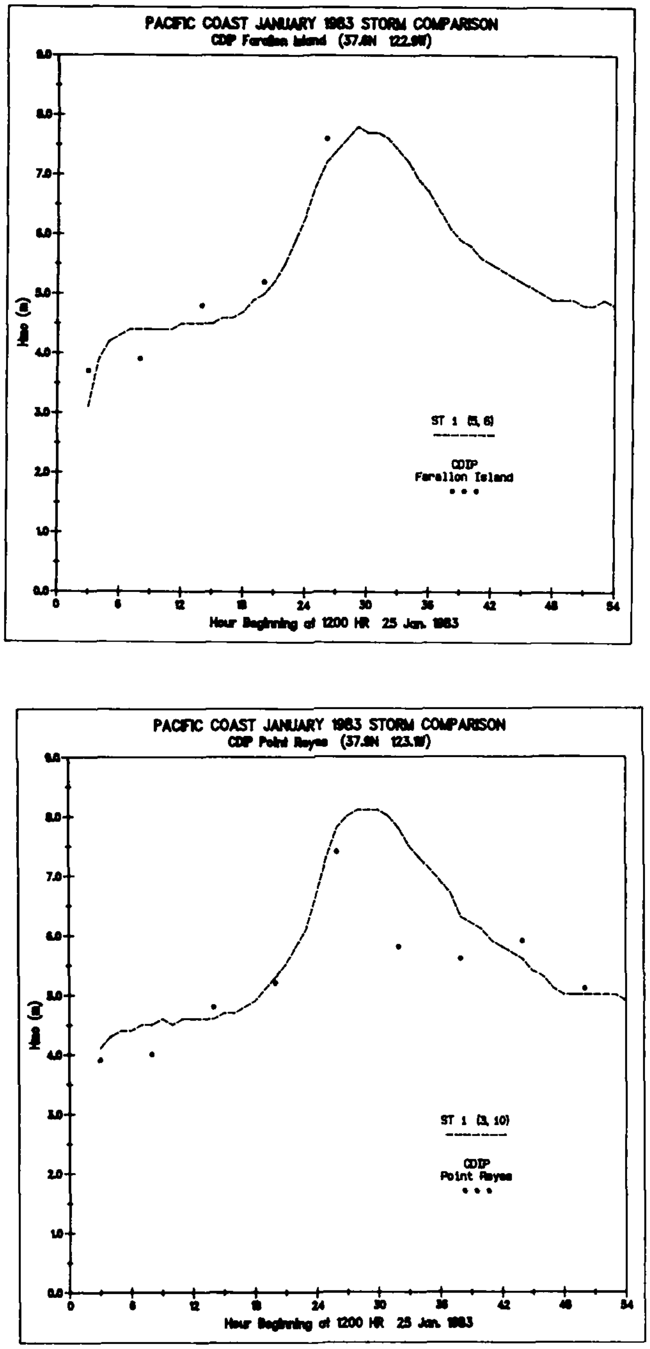


Figure 24. Wave height comparisons versus time at the two CDIP buoy locations

and simulated results. The maximum recorded and simulated wave heights (and accompanying peak spectral wave periods) for each storm sequence at all locations were compared in two cross plots. These comparisons were not true time paired observations between the two data sets, although the maximum lag time rarely exceeded 2 hr. This type of comparison will reflect all potential bias in the SHALWV results.

55. In general, wave height prediction is consistently within 10 percent of the measured storm's maxima. In the cross plot comparison depicted in Figure 25, only one simulated value was paired to the observed value. Considering the range of heights from 3 to 14.5 m, both tropical and extratropical wave estimates display the same approximate scatter. The peak periods also vary within about 15 percent depending on a storm's intensity (Figure 26). Similar to the comparison in Figure 25, only one simulated value was paired to the observed value in Figure 26. The scatter in these results may be more indicative of differences in wind field estimates. Two outlying measured T_p values (5.0 and 20.0 sec) were recorded at the same time other gages in the area (5.0 during Hurricane Gloria and 20.0 during the Pacific Coast storm) identified peak spectral periods more in line with the model's results.

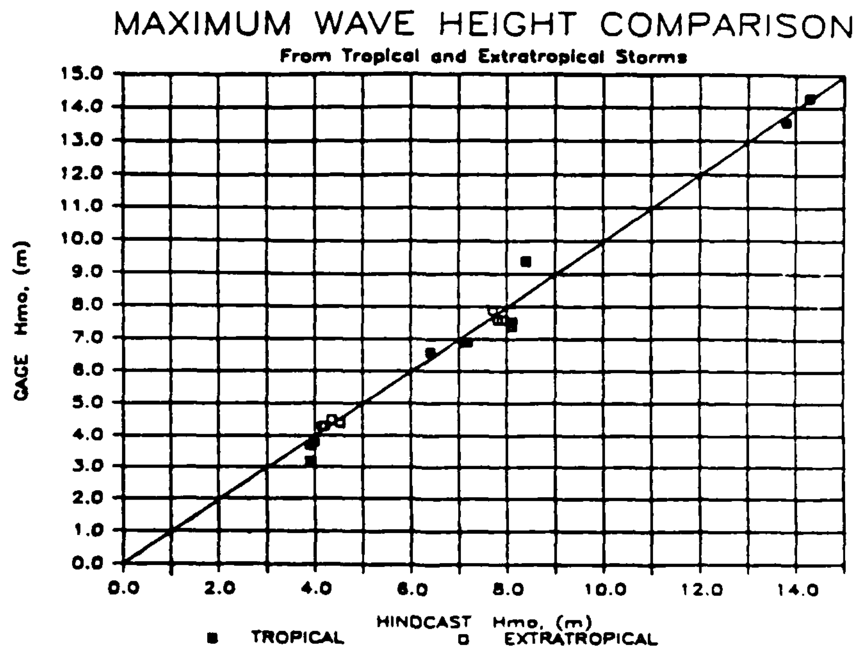


Figure 25. Cross plot comparison of maximum wave heights for each storm (tropical and extratropical) at each location

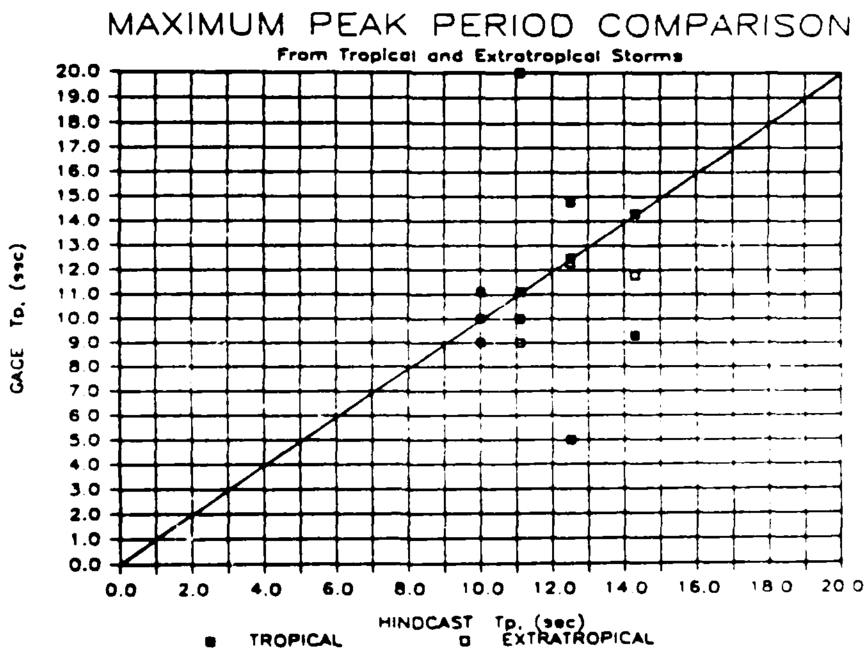


Figure 26. Cross plot comparison of the peak spectral period associated with the maximum wave height for each storm (tropical and extratropical) at each location

PART VII: SUMMARY

56. The goals of the study discussed in this report were to develop a working hurricane wave model that estimates wave conditions and spectral shapes similar to those in a prototype. In all wave hindcasts made, the wind fields were unlikely to be perfectly modeled, and this occurrence had an unknown effect upon wave prediction.

57. Comparison of the model to idealized wave growth without bias introduced from wind input conditions is shown in terms of deepwater nondimensional growth rate tests. The SHALWV results generally reproduce the JONSWAP results for nondimensional total energy and peak frequency over fetch. Temporal growth rates tend to show excellent agreement to JONSWAP estimates and are within ±10 percent of the Exact-Nonlinear results for nondimensional total energy and peak frequency.

58. Shoaling over a plane beach demonstrated that SHALWV is able to describe refraction effects on mean wave direction to within ±3 percent of the linear theory result.

59. SHALWV, as modified for hurricanes, predicts actual wave conditions within 10 to 15 percent of the measured values. The ARSLOE tests indicate that for fairly well described input conditions on a boundary, the model provides reproduction of wave conditions from relatively deep to fairly shallow water. Data from Hurricanes Camille, Edith, and Gloria show that the model reproduces extreme wave conditions in relatively deep and shallow water (for wavelengths of the peak period) given uncertainties and errors associated directly with the wind input. Spectral shapes in the storms appear similar to those measured for peak conditions. Final conclusions relative to Gloria can be reached upon rigorous reconstruction of the storm wind field.

60. Wave height comparisons in the California storm show that the model performs for large extratropical storms as well as for hurricanes and more moderate storms such as ARSLOE. No consistent bias was found in heights or periods. Given the spatial scales modeled, the variety of wind and wave input conditions, and the uncertainties in depth fields, wind fields, and measured wave fields, the model performs well. It is reassuring to note that the model can reproduce such a wide range of physical events (weak to strong, extratropical to hurricane) on such a variety of grid mesh sizes (3 to 55.6 km), size regions (1,600 sq km to the Gulf of Mexico), and input conditions (wind

field alone, observed wave and wind input, and hindcast from separate wave and wind models). The results were obtained without tuning of the drag coefficient for the air-sea interaction in the model, without tuning parametric formulations, and without site-specific tuning of a bottom friction coefficient.

61. The agreement found over the range of conditions tested provides indication of model validation to the error level of input parameters. Testing of the model is continuing to build up a larger body of comparisons for purposes of evaluating model accuracy. Possibilities for improving the model will be identified and incorporated into this report as an additional appendix when they become available.

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